STUDIES ON SINGLE BATCH TRANSFER OF LHC TYPE BEAMS BETWEEN THE CERN PS BOOSTER AND THE PS

A. Blas, C. Carli, A. Findlay, R. Garoby, S. Hancock, K. Hanke, B. Mikulec M. Schokker
CERN, Geneva, Switzerland

Abstract

At present, for most LHC type physics beams, six buckets of the PS operated with harmonic number h=7 are filled in two transfers, and each of the PS Booster rings provides only one bunch. The scheme presented aims at replacing the double batch transfer by a single batch transfer and is of interest (i) for the nominal 25 ns LHC beams once the Booster injection energy has been increased after completion of Linac4 and (ii) already now for 50 ns and 75 ns LHC beams less demanding for the Booster in terms of beam brightness. Two bunches with the correct spacing must be generated in the Booster rings by superposition of an h=2 RF system and a smaller h=1 component. Theoretical considerations and first experimental results will be presented.

INTRODUCTION

At present, for most LHC type physics beams, the PS is filled with two batches [1], spaced by 1.2 s, from the PS Booster. Exceptions are beams for special LHC fillings [2] with few bunches and large spacings, where every bunch in the LHC corresponds to one bunch in the PSB. For the generation of LHC type beams with double batch transfer, every (out of the four superimposed) PSB rings produces one bunch. Six out of seven PS buckets are filled with beam, in general by transferring first four bunches and 1.2 s later two more bunches. This double batch transfer is required to achieve the beam brightness required for nominal LHC operation with the present Linac2 as PSB injector. Note that every bunch injected into the PS is split in successive steps into several (up to twelve for nominal 25 ns LHC trains) bunches.

Studies on the generation of LHC type bunch trains with single batch PSB to PS transfer are motivated to shorten LHC filling for the following cases:

- Linac4 [3, 4], a new H^- linear accelerator under construction at CERN will allow increasing the PSB injection energy from 50 MeV to 160 MeV and replacing the conventional multi-turn injection with betatron stacking by a charge exchange injection. The aim is to increase the PSB performance and, in particular, the beam brightness such that nominal LHC beams can be produced with single batch PSB to PS transfer. The studies presented here have been triggered by investigations on the PSB upgrades for Linac4.
- Many variants of LHC beams, like e.g. bunch trains with nominal bunch population, but a bunch spacing increased from 25 ns to 50 ns or 75 ns, require a beam brightness achievable already now with Linac2.

After theoretical considerations on the beams required, first machine experiments on the generation in the PSB and a successful transfer test have taken place in 2008. The aim for the next 2009 run is to set up single batch transfer to generate LHC bunch trains with 50 ns and 75 ns bunch spacings with shorter PS cycles.

THEORETICAL CONSIDERATIONS

The procedure for PSB to PS single batch transfer for the generation of LHC bunch trains is sketched in Fig. 1. Each of three PSB rings provides two bunches to fill six out of seven PS buckets. Since the PS is operated with harmonic $h_{PS} = 7$ [1], the 327 ns spacing between buckets is larger than half of the PSB circumference (the circumference of the PSB is one fourth of the PS). The PSB ejection kicker has to fire in the shorter of the two unequal gaps between bunches and this becomes the limitation for the maximum possible bunch length of about 140 ns.

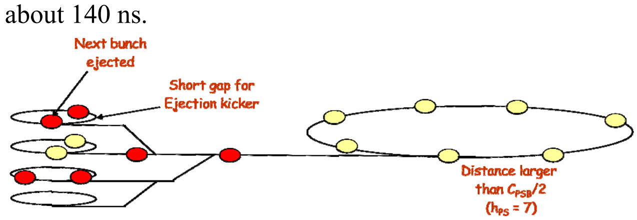

Figure 1: PSB to PS single batch transfer for the generation of LHC beams.

The appropriate bunch spacing cannot be obtained with a pure $h_{PSB} = 2$ RF system in the PSB, and another harmonic needs to be added. The $h_{PSB}=2$ voltage is assumed to be set to the maximum value of $V_{h=2} = 8$ kV. The best first harmonic voltage is somewhere between the following two extreme cases:

- $V_{h=1} = 3.6$ kV would generate the appropriate spacing between the centres (stable points) of the PSB buckets. However, the asymmetry introduced makes that the center of gravity moves even further than the bucket center.
- $V_{h=1} = 2.5$ kV and a longitudinal emittance of about 1 eVs yields the situation shown in Fig. 2. The extension of the bunch, marked by vertical lines, is symmetric around points spaced by 327 ns.

Note that the maximum longitudinal emittance per bunch is limited by the ejection kicker rise time to about 1 eVs, which is significantly smaller than the 1.3 eVs of the present double batch transfer. This, together with the imperfect matching due to the bunch asymmetries, implies that the longitudinal gymnastics in the PS need to be carefully monitored and, possibly, blow-up has to be introduced before the bunch splittings.

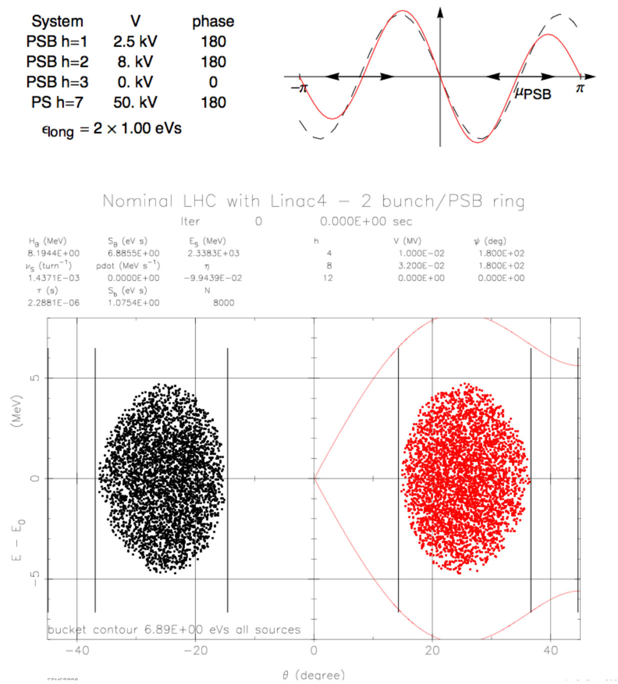

Figure 2: Bunches in the PSB at extraction.

The bunch lengths with single batch transfer need to be significantly shorter than with the presnt double batch scheme and, thus, transverse direct space charge effects are increased. This is not a concern for the generation of 50 ns and 75 ns trains with the present Linac2, since the intensity per bunch is sufficiently low. However, direct space charge effects are a concern for the generation of the nominal 25 ns trains with Linac4. The bunch length has to be increased quickly after transfer by e.g. bunch rotation (non-adiabatic), reduction of the RF voltage (quasi-adiabatic) or fast blow-up.

The asymmetry of the bunch shape could be reduced and the matching to the waiting PS buckets improved by a combination of additional first and third harmonic RF components. This option has not been pursued for the moment because of the additional complexity (no third harmonic RF available in the PSB at present); investigations concentrate on whether a scheme with only an additional h = 1 component gives satisfactory results.

FIRST EXPERIMENTAL RESULTS

Generation of the required bunch structure in the PSB

First PSB machine experiments have been focused on the generation of the required longitudinal structure without paying much attention to the transverse beam properties. The following steps are required before beam transfer:

- The longitudinal emittances are tailored by adjusting longitudinal blow-up and bunch splitting. The h = 1 voltage is not ramped down to zero during the splitting process, but kept at 2.5 kV (programmed value).
- The synchronization of the PSB w.r.t. the PS reference signal is carried out using the small h = 1 component of the beam signal to ensure correct positioning of the small and long gap between bunches.

Bunch shapes and a tomographic reconstruction of the longitudinal phase space are depicted in Fig. 3 for PSB ring 3. The asymmetry introduced by adding an h = 1 component is clearly visible. Careful investigations [6] (optimizing the convergence of the tomographic phase space reconstructions), triggered by an observed bunch asymmetry slightly larger than the expected one, led to the conclusion that the second harmonic voltage was only about $V_{h=2} \approx 7.2$ kV instead of the programmed 8 kV.

Concentrating on longitudinal aspects at high energy, this cycle had not yet been set up for optimizing beam brilliance. Thus, transverse emittances were too large to generate LHC 50 ns or 75 ns beams.

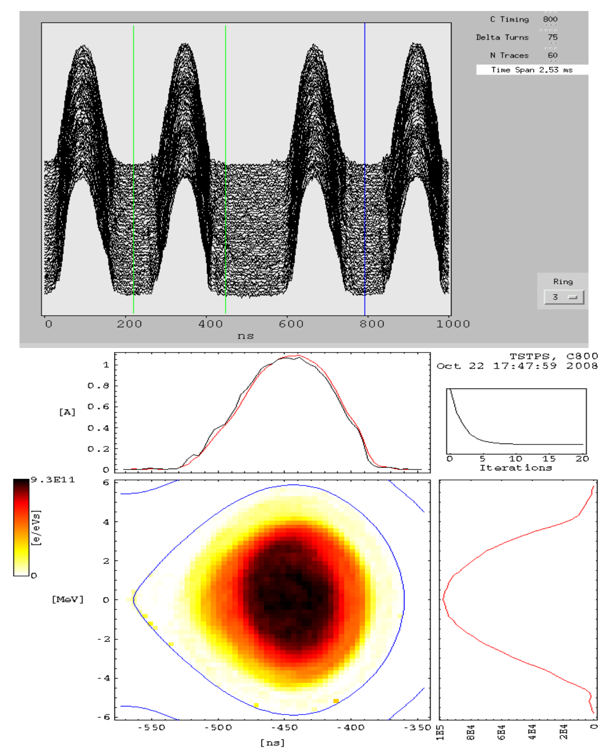

Figure 3: Bunch shapes and reconstruction of longitudinal phase of a beam prepared in ring 3 of the PSB.

Single batch transfer of a beam with the required bunch structure

In another experiment, the beam described was generated in the PSB and has been injected into the PS. Acquisitions of the longitudinal structure of the beam circulating in the PS are shown in Fig. 4. The lower intensity and, possibly the bunch shape oscillations of the two rightmost bunches from PSB ring 2 are caused by losses in the transfer line due to bad steering, which could not be corrected properly due to lack of time. All bunches are injected with small position oscillations, dominated even by a contribution common to all bunches, which could be corrected by readjusting relative phases of the PSB and the PS.

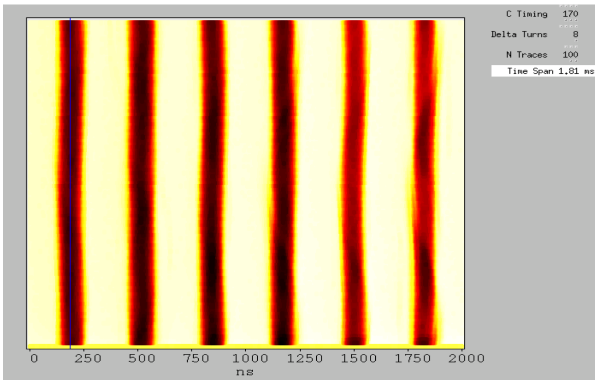

Figure 4: Time evolution of the longitudinal profiles of bunches injected into the PS.

Generation of the beam required for 50 ns LHC type beams

After successful experimental tests concentrating on longitudinal aspects, the low energy part of the PSB cycle has been optimized for highest brightness applying the standard ingredients:

- Use of a double harmonic RF system, both operated with about 8 kV in antiphase for bunch lengthening to reduce maximum direct space charge tune spreads.
- Dynamic working point with high (zero intensity) tunes at injection to create space for the large direct space charge tune spread of the order of 0.3. During the acceleration, the tune spread decreases and the zero intensity tunes are lowered. Proper compensation of transverse resonances up to order three is mandatory for maximum performance.

The transverse brightness needed (two bunches per ring, each with $0.81\text{x}10^{12}$ protons within normalized transverse rms emittances of 2.5 µm) for the generation of 50 ns bunch trains with nominal bunch population in the PS has been demonstrated. The longitudinal emittance was probably slightly overestimated. This beam has the same brightness than the one needed for the generation of the nominal 25 ns LHC beam with double batch transfer between the PSB and the PS.

SUMMARY AND OUTLOOK

First theoretical investigations and successful machine experiments have taken place in view of generating LHC bunch trains in the PS with single batch transfer between the PSB and PS. The aim is to shorten the PS cycles generating LHC bunch trains and, finally, to shorten LHC filling. Such a scheme is the baseline for the generation of the nominal 25 ns LHC beam during the Linac4 era, and it is of interest already now with Linac2 for 50 ns and 75 ns LHC beams as well as for lower intensity 25 ns LHC beams.

During the last run, only the generation of the appropriate bunch structure in the PSB and transfer to the PS has been demonstrated. The elaborate gymnastics needed to generate the LHC bunch structure in the PS has not yet been tested. This deserves particular attention, since the asymmetric bunches cannot be perfectly matched to the buckets and the longitudinal emittance of the PSB bunches is smaller than today with double batch transfer. Setting-up of PSB and PS for 75 ns and 50 ns LHC bunch trains will be the next steps:

- First efforts will concentrate on 75 ns trains, as a first step towards 50 ns trains which are of higher potential interest for the LHC. After transfer, moderate fast blow-up will be applied to generate the appropriate longitudinal emittance and remove structure from matching imperfections.
- Optimum bunch lengths for smallest transverse emittances have to be determined empirically. Beam properties obtained first before transfer in the PSB and then after splitting in the PS have to be measured carefully.
- Generation of 50 ns bunch trains are of higher potential interest for the LHC. More longitudinal blow-up is required prior to the first splitting, if one aims at executing all gymnastics with the present nominal parameters.
- Transverse direct space charge effects to be expected with Linac4 can be assessed with only one bunch per PSB ring having the lower longitudinal emittance required for single batch transfer. Injecting such a bunch in the PS and measuring transverse emittances will allow to test and compare mitigation measures against space charge.

REFERENCES

[1] R. Garoby, S. Hancock, J.L. Vallet , Demonstration of Bunch triple Splitting in the CERN PS, Proceedings of EPAC 2000 (Vienna).

[2] B. Mikulec, A. Blas, C. Carli, A. Findlay, K. Hanke, G. Rumolo, J. Tan, LHC Beams from the CERN PS Booster, these proceedings.

[3] M. Benedikt, J. Tan, Low-Intensity Beams for LHC Commissioning from the CERN PS-Booster, Proceedings of EPAC 2006 (Edinburgh).

[4] F. Gerigk, M. Vretenar (editors), Linac4 technical design report, CERN-AB-2006-084 ABP/RF.

[5] F. Gerigk, C. Carli, R. Garoby, K. Hanke, A. Lombardi, R. Maccaferri, S. Maury, C. Rossi, M. Vretenar, Construction Status of Linac4, these proceedings.

[6] S. Hancock, private communications